

Clustering of Far-Infrared Galaxies in the AKARI All-Sky Survey

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We present the first measurement of the angular two-point correlation function for AKARI 90- μ m point sources, detected outside of the Milky Way plane and other regions characterized by high Galactic extinction, and categorized as extragalactic sources according to our far-infrared-color based criterion (Pollo et al. 2010). This is the first measurement of the large-scale angular clustering of galaxies selected in the far-infrared after IRAS measurements. Although a full description of clustering properties of these galaxies will be obtained by more detailed studies, using either spatial correlation function, or better information about properties and at least photometric redshifts of these galaxies, the angular correlation function remains the first diagnostics to establish the clustering properties of the catalog and observed galaxy population. We find a non-zero clustering signal in both hemispheres extending up to ~ 40 degrees, without any significant fluctuations at larger scales. The observed correlation function is well fitted by a power law function. The notable differences between a northern and southern hemisphere are found, which can be probably attributed to the photometry problems and point out to a necessity of performing a better calibration in the data from southern hemisphere.

Key words: galaxies: clustering; large scale structure; dust; infrared; cosmology.

1. Introduction

According to the now widely accepted paradigm of the gravitational instability theory, galaxies formed and evolved inside dark matter halos. These haloes grew and merged under the effect of gravity, starting from the primordial almost homogeneous distribution, which is imprinted in the cosmic microwave background see, e.g., White and Rees (1978). Analysis of the galaxy clustering is then believed to be the key to understand the evolution of the underlying dark matter field, and hence the Universe itself. It is therefore an important issue to understand the bias between the distribution of galaxies and the underlying dark matter density field, and how it depends on galaxy properties.

The Infrared Astronomical Satellite (IRAS: Neugebauer et al. 1984) has brought a great amount of statistics. Especially in cosmology, the IRAS Point Source Catalog (PSC) provided a great homogeneous dataset of galaxies which has driven statistical studies drastically. A vast number of studies have been done based on IRAS galaxies. Early studies were based on the angular correlation (Rowan-Robinson and Needham 1986; Lahav et al. 1990; Babul and Postman 1990; Liu et al. 1994). Later, thanks to various IRAS redshift surveys (e.g., Rowan-Robinson et al. 1991; Strauss et al. 1992; Fisher et al. 1995; Saunders et al. 1990), tremendous progress has been brought in the spatial distribution or correlation function analysis (e.g., Efstathiou et al. 1990; Saunders et al. 1992; Hamilton 1993; Fisher et al. 1994; Peacock

et al. 1997). In these studies, IR galaxies were used as a tracer of mass distribution in galaxies, explicitly or implicitly.

However, this might not be regarded as an appropriate assumption anymore, since it was found that the amount of dust in galaxies is not strongly correlated to the stellar mass (e.g., Iyengar et al. 1985; Tomita et al. 1996). Indeed, a significant relative bias of IRAS galaxies to optical ones was found (e.g., Babul and Postman 1990; Lahav et al. 1990; Peacock et al. 1994). Nowadays, the IR emission from galaxies is known to be a good tracer of star formation activity, especially for actively star-forming galaxies, through the heating of dust grains by OB stars (e.g., Buat et al. 2007; Takeuchi et al. 2010; Murphy et al. 2011). Therefore, in a modern context, the large-scale structure of dusty galaxies is regarded as the star-formation density field in galaxies, which may be important to connect the dark matter field and star formation activity (e.g., Malek et al. 2010; Amblard et al. 2011).

This view has been supported by a vast number of analysis of clustering of infrared galaxies at scales up to a few degrees in various surveys. After IRAS, IR correlation function have been mainly estimated based on deep surveys. Gonzalez-Solares et al. (2004) estimated the angular correlation function of ISO 15- μ m galaxies in the European Large-Area Infrared Space Observatory (ELAIS) S1 survey. From ISO deep surveys, Matsuhara et al. (2000) and Lagache et al. (2000) performed a power spectrum analysis of the diffuse FIR background and discovered fluctuation due to the large-scale clustering of dusty galaxies. Subsequently, angular clustering analyses of Spitzer surveys were presented (e.g., Oliver et al. 2004; de la Torre et al. 2007; Gilli et al. 2007; Magliocchetti et al. 2008). These works were mainly based

on MIR data, but thanks to Herschel, recently results from longer wavelengths have been gradually reported (e.g., Mad-dox et al. 2010; Cooray et al. 2010; Amblard et al. 2011; Magliocchetti et al. 2011; Planck Collaboration et al. 2011).

After many years since IRAS, the advent of AKARI (ASTRO-F) opened new possibilities to explore the whole sky in the far infrared, as a survey-oriented space telescope at MIR and FIR (Murakami et al. 2007). The primary purpose of the AKARI mission is to provide second-generation infrared (IR) catalogs to obtain a better spatial resolution and a wider spectral coverage than the IRAS catalog. All-sky surveys and some pointed deep observations were made by AKARI. In this work, we present the first measurement of the angular correlation function for FIR-selected extragalactic sources from the AKARI All-Sky Survey. One related work on AKARI Deep Field-South (ADF-S) has been presented (Małek et al. 2010), but in this work, we made an analysis on much wider area data to see the large-angle correlation.

This article is organized as follows: in section 2, we present the selection of data used for this analysis. In section 3, we present and discuss the properties of the angular correlation function of selected AKARI sources. We conclude in section 4.

2. Data

2.1 AKARI

AKARI is a Japanese astronomical satellite which was aimed at performing various large-area surveys at the IR wavelengths, from NIR to FIR, with a wavelength coverage of 2–160 μm , as well as pointed observations.¹ AKARI is equipped with a cryogenically cooled telescope of 68.5 cm aperture diameter and two scientific instruments, the Far-Infrared Surveyor (FIS; Kawada et al. 2007) and the Infrared Camera (IRC; Onaka et al. 2007).

2.2 AKARI all-sky surveys

Among most significant astronomical observations performed by AKARI, an all sky survey with FIS and IRC has been carried out; it is referred to as the AKARI All-Sky Survey. It is the second ever performed all sky survey at FIR, after IRAS. The FIS scanned 96 % of the entire sky more than twice in the 16 months of the cryogenic mission phase. In March 2010, the AKARI/FIS Bright Source Catalogue v.1.0 has been released to the scientific community. It contains in total 427 071 point sources measured at 65, 90, 140, 160 μm . Hereafter, we use a notation S_{65} , S_{90} , S_{140} and S_{160} for flux densities in these bands.

The position accuracy of the FIS sources is 8'', since the source extraction is made with grids of this size. Effective size of the point spread function of AKARI FIS in FWHM is estimated to be $37 \pm 1''$, $39 \pm 1''$, $58 \pm 3''$, and $61 \pm 4''$ at 65 μm , 90 μm , 140 μm , and 160 μm , respectively (Kawada et al., 2007). Errors are not estimated for each individual source, but instead they are in total estimated to be 35 %, 30 %, 60 %, and 60 % at 65 μm , 90 μm , 140 μm , and 160 μm , respectively (Yamamura et al., 2010).

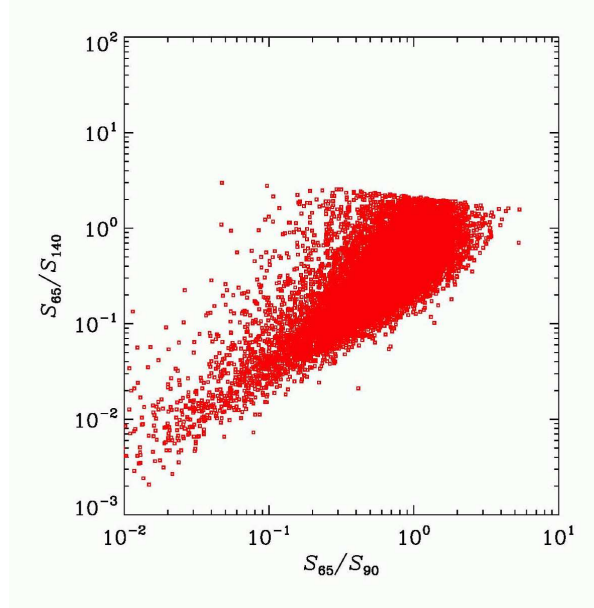


Fig. 1. Color selection of AKARI FIS 90 μm sources. Galaxy candidates are presented by dots.

Since FIS has sensitivity at longer wavelengths than IRAS, we can expect a different composition of sources: we should see objects with cool dust which were difficult to detect by IRAS bands. Consequently, the clustering properties of galaxies selected from the AKARI FIS catalogs can also be different from the corresponding IRAS galaxies.

2.3 Selection of Extragalactic Sources

As mentioned before, the complete FIS All-Sky Survey contains 427 071 point sources. Since the primary detection was performed at 90 μm , all sources have a flux measurement at least at this band.

In the further analysis, we restrict ourselves to the area of low contamination of the Galactic FIR emission ($I_{100} \leq 5 \text{ MJy sr}^{-1}$) measured from the Schlegel maps (Schlegel et al. 1998), in order to avoid contamination by sources from Galactic plane and Galactic cirrus emission. This procedure excludes also areas of both Magellanic Clouds.

In order to assure a good quality of AKARI photometric measurements, we additionally mask the data, restricting ourselves only to the parts of the sky which were scanned by AKARI at least three times.

This masking procedure leaves us with 13537 sources in the northern hemisphere and 12096 sources in the southern hemisphere, which gives in total 25 633 sources.

In Pollo et al. (2010), we have presented a method to classify the AKARI sources in the color-color diagrams only from FIS bands. In order to be able apply this method to select candidates for extragalactic sources in the following analysis, we further restrict ourselves only to sources with the full four-band FIS color information, which is available for 9700 among already selected sources from the northern hemisphere and for 8387 from the southern hemisphere. Then, we applied our color-based method to select candidates for the extragalactic sources in the low-extinction area. The result of this selection on the color-color plane is presented in Figure 1. Sky distribution of all 18 087 sources left

Detailed information on the AKARI project, instruments, data and important results can be found via URL: <http://www.ir.isas.ac.jp/ASTRO-F/index-e.html>.

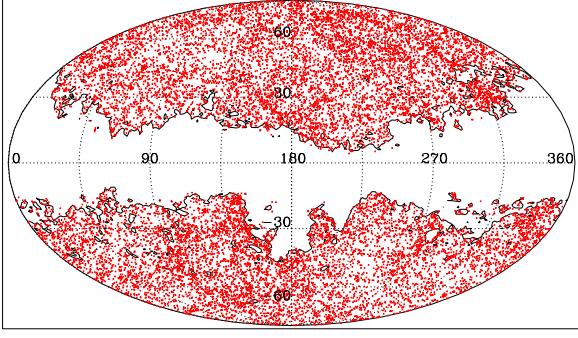


Fig. 2. Sky distribution of AKARI FIS galaxies selected by colors. Only galaxies located on the sky region with $I_{100} < 5 \text{ MJy sr}^{-1}$ are used in this analysis.

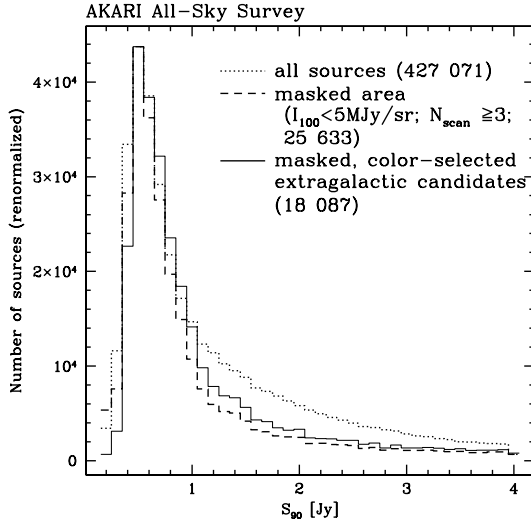


Fig. 3. Renormalized histograms of S_{90} fluxes of AKARI FIS sources. The dotted line corresponds to the sources from the complete sample. Sources from the masked areas, i.e. areas with Galactic cirrus emission lower than 5 MJy sr^{-1} and scanned by AKARI at least three times, are denoted by solid line. Sources from masked area, selected as galaxy candidates by our far infrared color-based criterion, are shown by dashed line.

after masking and selection procedures is presented in Figure 2. This sample is then used for the analysis presented in the next sections.

The results of our selection procedure on S_{90} luminosities of the sample can be observed in Figure 3 which presents the renormalized histograms of S_{90} for the complete sample, masked sample and masked sample of color-selected galaxies. We can see that the masking procedure significantly reduces the bright tail of the distribution by the removal of the brightest Milky Way sources. The color selection seem to reverse partially this effect, which is a result of the fact that only sources with full color information, systematically brighter, were used for this procedure. A few remaining sources with the value of S_{90} lower than 0.2, which is below the 3σ detection limit of AKARI, were also excluded from the further analysis.

3. Clustering of AKARI All-Sky Survey Galaxies

3.1 Method

The two-point angular correlation function, $\omega(\theta)$ is defined as the excess probability above random that a pair of galaxies is observed at a given angular separation θ (Peebles 1980). It is the simplest statistical measurement of clustering, as a function of angular scale, and it corresponds to the second moment of the distribution. Various recipes, aiming at minimizing of different sorts of observational biases, have been proposed to estimate two-point correlation functions from galaxy surveys. In this work, we adopt the angular version of the Landy-Szalay estimator (Landy and Szalay 1993), that expresses $\omega(\theta)$ as

$$\omega(\theta) = \frac{N_R(N_R - 1)}{N_G(N_G - 1)} \frac{GG(\theta)}{RR(\theta)} - \frac{N_R - 1}{N_G} \frac{GR(\theta)}{RR(\theta)} + 1 \quad (1)$$

In this expression, N_G and N_R are the total number (equivalently, the mean density may be used) of objects respectively in the galaxy sample and in a catalog of random points distributed within the same survey volume and with the same photometric mask applied as the one used for the real data. $GG(\theta)$ is the number of independent galaxy-galaxy pairs with separation between θ and $\theta + d\theta$; $RR(\theta)$ is the number of independent random-random pairs within the same interval of separations and $GR(\theta)$ represents the number of galaxy-random pairs.

Different ways of estimating errors on two-point correlation functions have been used in the literature (Hamilton 1993; Fisher et al. 1994). Since our aim in this case is the first diagnosis of the galaxy clustering in the AKARI data, we do not apply any refined error estimation method, and we show only the Poissonian errors. Hence, it should be remembered that they would indicate the lower limit on the actual errors, since they reflect only the information related to the statistical properties of the sample (see, e.g., Fisher et al. 1994).

In practice, both spatial and angular correlation function are usually well fitted by a power-law model:

$$\omega(\theta) = A_w \theta^{1-\gamma}, \quad (2)$$

with $1 - \gamma$ being the slope of the correlation function (γ itself is then to the slope of a corresponding spatial correlation function) and A_w is the normalization of the correlation function.

3.2 Clustering of Sources in Southern and Northern Hemispheres

The angular correlation function in the linear scale is shown, separately for the northern and southern Galactic hemispheres, in the left and right panels, correspondingly, of Figure 4. In both hemispheres we measure a positive signal up to $\theta \sim 40$ degrees. For separations larger than ~ 40 degrees, the signal remains negative without any significant fluctuations. This roughly agrees with the first clustering measurement for the IRAS sources (Rowan-Robinson et al. 1986). In contrast to what was seen in the first IRAS data, we do not observe any strong difference in the shape of the correlation function between northern and southern sky, in particular between 10 and 40 degrees. However, there are

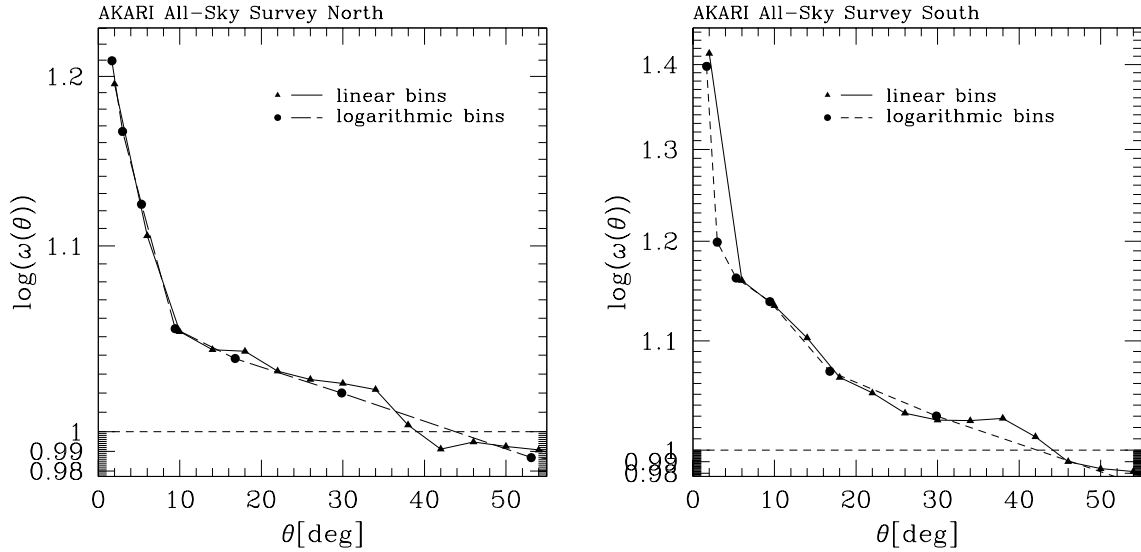


Fig. 4. Angular correlation function, in linear and logarithmic bins, in the northern (left panel) and southern (right panel) hemisphere of the AKARI All-Sky Survey. In both panels linear bins are marked by full triangles, connected by solid line, while logarithmic bins are shown as full circles connected by dashed line. Note a difference in scale of both panels.

notable differences: the most important is that sources in the southern sky seem to be, at all scales, more strongly clustered than those observed in the northern sky.

Since this feature does not correspond to any feature ever measured in wavelengths, the most probable explanation of this fact would be an imperfect calibration of photometry of the data from the southern hemisphere, possibly being remnants of South Atlantic Anomaly. This was also realized in case of the first IRAS data (e.g., Rowan-Robinson and Needham 1986). Our results indicate, then, that the All Sky Survey data should be still approached with some caution.

The difference between both hemispheres becomes even clearer when we a power-law fit to the angular correlation function is made, as shown in Figure 5. Both correlation functions can be fitted by the power-law function reasonably well on the scale 1-40 degrees, but some scale-dependant deviations are clearly visible in the function measured in the southern hemisphere. Both functions have very similar slope $\gamma = 1.8 \pm 0.1$, higher than previously measured for these scales for FIR galaxies. From this plot it is also well visible that southern galaxies seem to be much more strongly clustered than northern ones, with the clustering length $A_w = 0.24 \pm 0.01$ degrees, while in the northern hemisphere we measure $A_w = 0.16^{+0.02}_{-0.01}$.

3.3 Flux density dependence of clustering in the AKARI All-Sky Survey North

Dependence of clustering properties of AKARI FIS galaxies on their flux density in $90 \mu\text{m}$ is presented in Figure 6 and Table 1. A general trend is in the agreement with the behavior expected from the hierarchical model of structure formation, and with other similar measurements: brighter galaxies are clustered stronger than fainter ones, and the clustering length rises with the limiting flux density. The reversal of this trend can be observed in case of the two faintest samples: galaxies with $S_{90} > 0.5$ Jy seem to be less clustered than the complete sample limited by $S_{90} > 0.2$ Jy. This latter

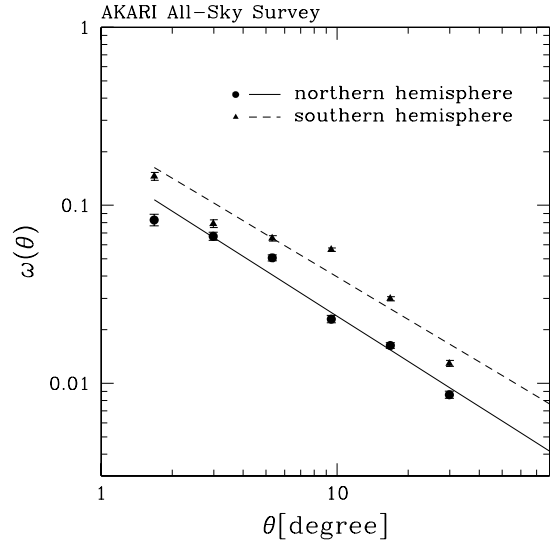


Fig. 5. Power-law fit to the angular correlation function of extragalactic sources, measured in the northern (full circles, solid line) and southern (full triangles, dashed line) hemisphere of the AKARI All-Sky Survey. Points correspond to the measurements in the logarithmic bins, while lines show the best power-law fit.

result might indicate that the photometric measurements are systematically biased for some of the faintest sources. The clustering of the brightest subsample is the strongest, and the best-fitted slope is less steep than in case of fainter sources, which is more similar to other far-infrared surveys.

4. Summary and conclusions

We present the first measurement large-scale clustering of the far-infrared galaxies in the AKARI FIS All-Sky Survey. We have measured the angular two-point correlation function

Table 1. Clustering properties of four subsamples with different flux density S_{90} in the AKARI All-Sky Survey North.

limiting S_{90} [Jy]	Number of galaxies	A_w [deg]	γ
0.2	8472	$0.16^{+0.02}_{-0.01}$	1.8 ± 0.1
0.5	5493	0.16 ± 0.02	1.9 ± 0.1
1.0	2233	$0.24^{+0.05}_{-0.04}$	1.9 ± 0.2
1.5	1282	$0.30^{+0.07}_{-0.05}$	$1.7^{+0.1}_{-0.1}$

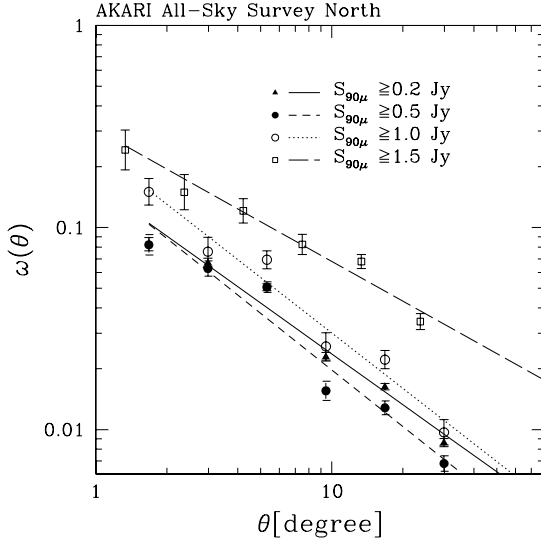


Fig. 6. Angular correlation function in the AKARI All-Sky Survey North - comparison of subsamples with different limits of flux density S_{90} . Points correspond to the measurements in the logarithmic bins and lines show the best power-law fit. Full triangles and solid line correspond to the whole sample, i.e. $S_{90} > 0.2$ Jy. Full circles and short-dashed line correspond to the sample with a limit $S_{90} > 0.5$ Jy. Open circles and dotted line correspond to the sample limited by $S_{90} > 1$ Jy. The brightest sample $S_{90} > 1.5$ Jy is shown by open squares and long-dashed line.

for the $90 \mu\text{m}$ -selected sample of galaxies in the northern and southern hemisphere. Our conclusions are as follows:

- 1) We find a positive signal up to ~ 40 degrees, in all scales between 1 and 40 degrees reasonably well fitted by a single power-law function with $\gamma \sim 1.8 \pm 0.1$, and the amplitude $A_w = 0.16^{+0.02}_{-0.01}$ for the northern and 0.24 ± 0.01 for the southern hemisphere.
- 2) We suggest that this north-south difference might be a result of calibration problems in the data due to the southern hemisphere, possibly related to the South Atlantic Anomaly.
- 3) We observe the increase of clustering length with increasing flux density limit of the sources, in accordance with expectations for a sample of relatively nearby galaxies.

This measurement of clustering for dusty galaxies will make it possible to relate the density field of galaxies with hidden strong star-forming activity to the general population of galaxies, i.e., the relative bias of dusty star-forming galaxies.

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